Circulatory adjustments in the Giraffe - Lessons to be learned for the fighter pilot?

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Autumn 2017

Introduction

In modern high-performance flights such as aerobatic aircrafts and fighter aircrafts, accelerations to the cardiovascular system can occur well beyond the normal level of +1Gz experienced at rest. Accelerations in the head-to-foot direction (+Gz) induces cranial hypotension and impose alterations to the cardiovascular system, which must then work to provide an adequate supply of blood to the eyes and the brain. This significant stress may be sufficient to critically impair cerebral blood flow (CBF), possibly leading to issues such as visual impairments and, lastly, G-induced loss of consciousness (G-LOC).

Exposure to accelerations higher than +1Gz and disturbances in the distribution of pressure in arterial and venous systems induces blood shifts towards critically dependent parts. In attempting to compensate for such effects of reduced CBF and to moderating the fall in blood pressure (BP) due to high +Gz exposure, reflex cardiovascular responses – tachycardia and peripheral vasoconstriction – naturally occurs (Green, 2006). These issues reflect the impact of alterations in the hydrostatic force, represented by the increase in weight of the column of blood above and below the heart. This is relevant for understanding the implications of cardiovascular exposure due to increased G force and the countermeasures a fighter pilot may use for minimizing its effects.

With the distance of approximately two meters from the heart to the brain, despite the strong heart to overcome the huge hydrostatic force generated by the neck blood column, giraffes seemly undergo the same syndrome as pilots in high acceleration when lifting neck from the ground. In fact, they will not faint because of their own special regulatory system to maintain cerebral circulation. Here, we will discuss the cardiovascular system of pilots during acceleration as well as the mechanism of giraffes' circulation adjustment system. Learning from the giraffes, we suggested several techniques against high G-loads that may decrease the likelihood of suffering from G-LOC and improve pilot performance.

Effects of acceleration on the cardiovascular system

A fundamental mechanism related to the exposure to acceleration relates to alterations in magnitude of the hydrostatic pressure (or force) (HP). The HP is the pressure applied by a "column of fluid and is proportional to the magnitude of the applied acceleration" (Newman, 2016). It is expressed following the formula below:

HP = *p.g.h*
where: HP = hydrostatic pressure
p = fluid density
g = acceleration due to gravity – $9.81 m.s^{-1}$
h = height of the fluid column

By increasing +Gz acceleration, there is an increase in hydrostatic gradient in the arterial and venous systems (Green, 2006). As a result, there is a reduction in the vascular pressure above the heart and an increase below the heart. In a person, the column of blood in the arterial system between the heart and the head is about 30cm in height. The blood density is about 1.06g/ml. Considering *h,* the hydrostatic pressure difference between the heart and the base of the brain of an adult in the upright posture is approximately 22 mmHg (millimeters of mercury). Considering that the heart-level blood pressure (BP) is 100 mmHg, the head-level BP is, then, 78 mmHg, at the femoral artery it is around 145 mmHg and at the ankle is about 195 mmHg. The pressure differential proportionally varies according to the magnitude of the applied acceleration. That means that at +2Gz and +4Gz the pressure differential will be 44 mmHg and 88 mmHg, respectively. If the intraocular pressure drops to around 15 mmHg, the pilot is susceptive to visual impairment. Further decreasing of pressure at brain can result in temporary unconsciousness. The model is established on the assumption that there is no vertical movement of the heart. However, in reality, the situation can be worse. Pilots exposed to high +Gz acceleration experience a descending diaphragm and heart of about 5cm from the original position, which will result in an extra pressure drop in the brain level of 20 mmHg.

In normal conditions, only changes in *h* will demand cardiovascular system's adaptation. This may happen when there are postural changes, i.e., when one goes from the prone to the upright position. However, by increasing acceleration in the head-to-foot axis, cardiovascular adaptations must compensate for the increase in hydrostatic gradient in the cardiovascular system.

Henceforth, the pressure differential between the heart and the brain can be increased either by changes in *h* or by increasing +Gz acceleration. The extra +Gz acceleration a pilot receives is typically decided by linear and radial acceleration of airplane and the centrifugal force.

Giraffe's circulatory adjustments

Rushmer (1947) has made an analogy with the cardiovascular dynamics of the giraffe for describing what a significant increase in the brain-heart hydrostatic barrier (*h*) would mean. His intention was to illustrate that, by increasing +Gz acceleration, the physiological equivalent to the orthostatic challenge encountered between heart and brain would be similar to having the human neck extended by a proportional amount (Figure 1). Thus, according to this analogy, if the pressure differential at +4Gz is 88 mmHg, the same pressure differential could be reached at +1Gz if the human neck was stretched to the form of a giraffe.

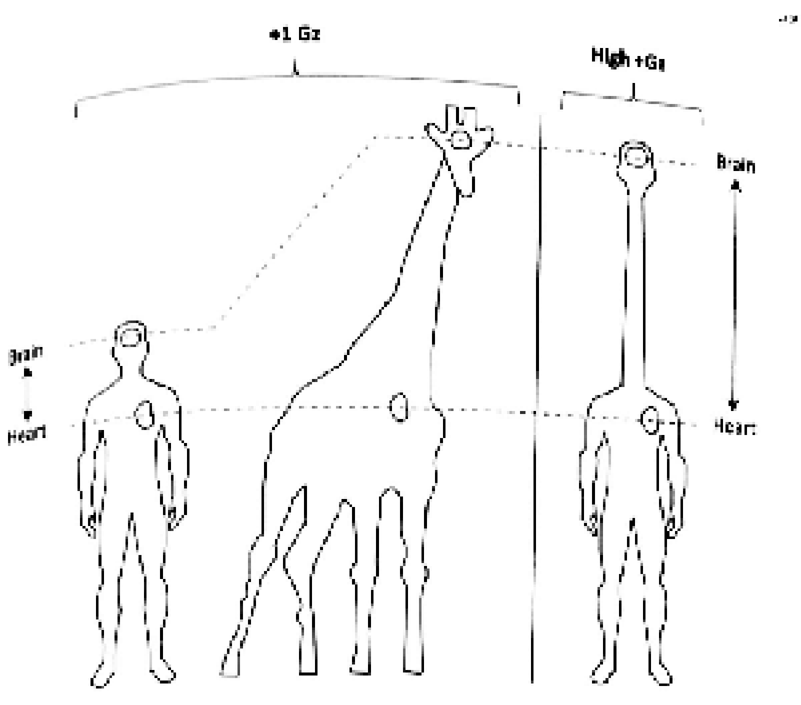

Figure 1. Human-giraffe comparison. (Retrieved from Newman, 2016; p. 59).

Despite the giraffe's increased hydrostatic pressure difference between heart and brain, several features of their circulatory system allow them to maintain an optimal cerebral perfusion pressure (CPP) – the net pressure gradient allowing cerebral blood flow to the brain. CPP is determined by the difference between mean arterial pressure (MAP) and the intracranial pressure (ICP) at the head (Munis and Lozada, 2000 as cited in Mitchell, Bobbitt & Devries, 2008). Thick arterial walls and abundant connective tissues allow them to overcome the pressure differential of about 118 mmHg for a distance of approximately 160 cm. During head-raising, the neck veins have a system of valves to prevent backflow of blood into the brain (Goetz et. Al., 1960). In addition, it was observed a non-collapsible 'venous' drainage channel that could enhance CPP and sustain CBF regardless of considerable decreases in MAP during head-raising (Mitchell, Bobbitt & Devries, 2008). Their legs are thin and the skin has adherent non-distensible properties, which minimizes peripheral pooling and assist in providing some hydrostatic countermeasures (Newman, 2016). Since vascular transmural pressure – the difference between intravascular and extravascular pressure –, distensibility of the vessel and the amount of blood available to fill it determines changes in intravascular pressure (Green, 2006), giraffe's legs characteristics and unique anatomical structures favor in dealing with increased HP differences, in spite of their size and elongated neck.

Lessons to be learned for the fighter pilot

The cardiovascular system stands for an extreme effect during exposure to high +Gz acceleration, resulting in a circulatory disturbance. Distribution of pressure in the arterial and venous system is changed and induce blood shifting downwards away from the brain.

To avoid G-induced loss of consciousness, arterial pressure at head level must be maintained during exposure to high G loads. There are several techniques to do that.

The first one is Anti-G Straining Maneuver, AGSM. This is a principal method to increase G tolerance above +5Gz. It is a forced exhalation effort against a closed glottis while tensing leg, arm and abdominal muscles. This increases the pressure to arterioles and veins, increasing peripheral vascular resistance, therefore reducing peripheral pooling and increasing arterial pressure at heart level. This is a learned maneuver which should be taught to the pilots, and may increase G tolerance to approximately +2Gz.

The second technique is the anti-G suit. It is a suit that the pilot wear and it will be pressurized with air during increases in +Gz force. This inflation will press legs and abdominal region of the pilot to create vasoconstriction, thus increasing arterial blood pressure. Increase in tissue pressure also adds mechanical pressure to veins, limiting venous pooling and favoring a shift of blood to the thorax, similarly to AGSM. Besides this, the heart is elevated upward so that the distance between brain and heart decreases. The anti-G suit can increase G-tolerance by another 0.5G - 1.0G.

The third technique is pressure breathing. It means that the pilot shall wear a jerkin which is inflated to the same pressure as the mask to increase the intrapulmonary pressure. The jerkin can counteract the high levels of pressures required for G protection and reduce the fatigue associated with the AGSM.

An equally important technique is muscular strength training. Research has shown that a 10 - 12 weeks weight-lifting program can increase G-duration tolerance approximately 50% (Wiegman, Burton and Forster).

The most effective method for increase G tolerance is postural modification, which means to decrease the vertical distance between brain and heart of the pilot. This can be done by, for example, setting a 30-degree seatback angle, a feature of the F-16 fighter aircraft. Some experimental airplanes have attempted to place the pilot in the prone position. An example is illustrated below in figure 2. The prone position significantly decreases the large +Gz impact, but it narrows the view of sight of the pilot and gives discomfort for a long flight mission. Thus has been shown impractical for real operations.

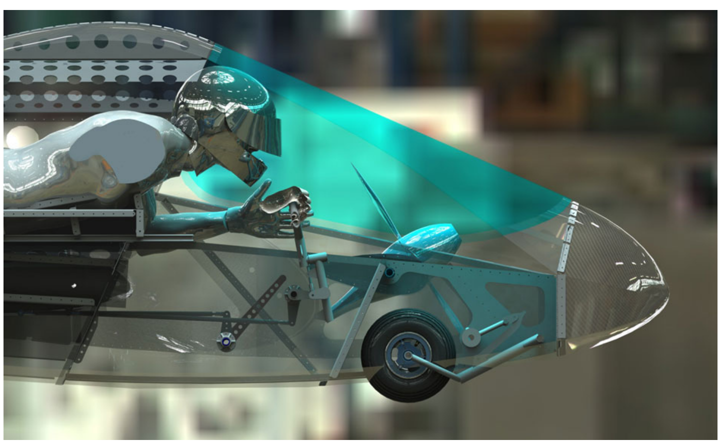

Figure 2: The Tangent EMG-5 with a prone position (Kampf, 2015).

Conclusion

The mechanisms fighter pilots use to increase G tolerance and maintaining arterial pressure at head level partially mimics some natural anatomical features of the giraffe that gives them the advantage in compensating for a high hydrostatic pressure difference between the heart and brain.

The giraffe has a powerful heart to ensure the normal cerebral pressure level due to its long neck, which also means the blood pressure at heart level would be incredibly high to compensate the hydrostatic pressure. Similarly, AGSM favors increasing arterial pressure at heart level of pilots to overcome the huge hydrostatic pressure caused by high acceleration.

Comparing to human, the vessels in lower limbs of giraffes are thicker and can prevent oedema in high pressure. The great extensibility of connective tissues and the adherent non-distensible properties of giraffe's legs seems to provide a hydrostatic countermeasure. Also, the natural tight skin works as a compressing tube to restrain peripheral blood pooling in the limbs. The anti-G suit, working just as the skin of the giraffe, is used to increase arterial blood pressure as well as to diminish venous pooling to favor a shift of blood to the thorax. It is unrealistic to shorten the neck length of pilots but, by pressing the abdomen, the heart is elevated, so that the distance between the heart and the brain is reduced, decreasing the difference in hydrostatic pressure.

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